genome, both of which highlight a trend toward genome compaction. This compaction can be seen clearly in the regions of the *Paramecium* genome shown in Figure 1. Coding sequences comprise 78% of the *Paramecium* genome, with an average of 352 nucleotides separating the stop codon of one gene and the start codon of the next. DNA sequences that direct transcription in ciliates have been studied little, and it will be interesting to learn whether these sequences are present within the coding regions of adjacent genes.

In a further reduction of non-coding sequence, *Paramecium* introns are shortened to an average length of only 25 base pairs. Given the overall minimization of non-coding sequences, it seems surprising that 80% of *Paramecium* genes contain introns, which are absent from most genes found in other compact genomes such as that of *S. cerevisiae* (see Figure 1). Introns may be necessary in *Paramecium* to facilitate efficient gene expression. Alternatively, intron loss may lead to a dire outcome. Meyer and colleagues [9,10] have shown that removal of sequences from the parental macronucleus leads to targeted deletion of the homologous region from the daughters' macronuclear genome as it forms. These deletion events are thought to be directed by a genome surveillance mechanism that uses homologous RNAs to compare the content of the micronuclear and macronuclear genomes [11]. Any micronuclear region not matching the parental macronuclear genome will be excised. The loss of an intron from the macronuclear gene copies could therefore lead to the imprecise removal of DNA from the corresponding micronuclear-derived locus during subsequent macronuclear development, effectively disabling the gene and disturbing the gene dosage balance.

Genome duplications have long been postulated to promote diversification [12], but duplicates must stick around long enough to allow specialization. Though the records of ancient duplications show that few of the genes from this latest event in *Paramecium* will be retained, this snapshot of a whole-genome duplication in decay has revealed the importance of gene dosage in slowing this process. Whether this extra time allows genes to diversify may be revealed in subsequent analyses. Fortunately, *P. tetraurelia* is one of 15 well-characterized sibling species whose divergence likely occurred after the most recent whole-genome duplication. This group of ciliates should become a rich source for investigating the nuances of both gene loss and specialization after duplication.

References

1. Blanc, G., Hokamp, K., and Wolfe, K.H. (2003). A recent polyploidy superimposed on older large-scale duplications in the Arabidopsis genome. Genome Res. *13*, 137–144.
2. Kellis, M., Birren, B.W., and Lander, E.S. (2004). Proof and evolutionary analysis of ancient genome duplication in the yeast *Saccharomyces cerevisiae*. Nature *428*, 617–624.
3. Meyer, A., and Van de Peer, Y. (2005). From 2R to 3R: evidence for a fish-specific genome duplication (FSGD). Bioessays *27*, 937–945.
4. Jaillon, O., Aury, J.M., Brunet, F., Petit, J.L., Stange-Thomann, N., Mauceli, E., Bouneau, L., Fischer, C., Ozouf-Costaz, C., Bernot, A., *et al*. (2004). Genome duplication in the teleost fish *Tetraodon nigroviridis* reveals the early vertebrate proto-karyotype. Nature *431*, 946–957.
5. Aury, J.M., Jaillon, O., Duret, L., Noel, B., Jubin, C., Porcel, B.M., Segurens, B., Daubin, V., Anthouard, V., Aiach, N., *et al*. (2006). Global trends of whole-genome duplications revealed by the ciliate *Paramecium tetraurelia*. Nature *444*, 171–178.
6. Seoighe, C., and Wolfe, K.H. (1999). Yeast genome evolution in the post-genome era. Curr. Opin. Microbiol. *2*, 548–554.
7. Prescott, D.M. (1994). The DNA of ciliated protozoa. Microbiol Rev. *58*, 233–267.
8. Eisen, J.A., Coyne, R.S., Wu, M., Wu, D., Thiagarajan, M., Wortman, J.R., Badger, J.H., Ren, Q., Amedeo, P., Jones, K.M., *et al*. (2006). Macronuclear genome sequence of the ciliate *Tetrahymena thermophila*, a model eukaryote. PLoS Biol. *4*, e286.
9. Meyer, E. (1992). Induction of specific macronuclear developmental mutations by microinjection of a cloned telomeric gene in *Paramecium primaurelia*. Genes Dev. *6*, 211–222.
10. Meyer, E., Butler, A., Dubrana, K., Duharcourt, S., and Caron, F. (1997). Sequence-specific epigenetic effects of the maternal somatic genome on developmental rearrangements of the zygotic genome in *Paramecium primaurelia*. Mol. Cell. Biol. *17*, 3589–3599.
11. Nowacki, M., Zagorski-Ostoja, W., and Meyer, E. (2005). Nowa1p and Nowa2p: novel putative RNA binding proteins involved in trans-nuclear crosstalk in *Paramecium tetraurelia*. Curr. Biol. *15*, 1616–1628.
12. Ohno, S. (1970). Evolution by Gene Duplication (New York: Springer-Verlag).
13. Stein, L.D., Mungall, C., Shu, S., Caudy, M., Mangone, M., Day, A., Nickerson, E., Stajich, J.E., Harris, T.W., Arva, A., *et al*. (2002). The generic genome browser: a building block for a model organism system database. Genome Res. *12*, 1599–1610.
14. Arnaiz, O., Cain, S., Cohen, J., and Sperling, L. (2006). ParameciumDB: a community resource that integrates the *Paramecium tetraurelia* genome sequence with genetic data. Nucleic Acids Res. DOI: 10.1093/nar/gkl777.
15. Stover, N.A., Krieger, C.J., Binkley, G., Dong, Q., Fisk, D.G., Nash, R., Sethuraman, A., Weng, S., and Cherry, J.M. (2006). Tetrahymena Genome Database (TGD): a new genomic resource for *Tetrahymena thermophila* research. Nucleic Acids Res. *34*, D500–D503.
16. Hirschman, J.E., Balakrishnan, R., Christie, K.R., Costanzo, M.C., Dwight, S.S., Engel, S.R., Fisk, D.G., Hong, E.L., Livstone, M.S., Nash, R., *et al*. (2006). Genome Snapshot: a new resource at the Saccharomyces Genome Database (SGD) presenting an overview of the Saccharomyces cerevisiae genome. Nucleic Acids Res. *34*, D442–D445.

[1]Department of Biology, Washington University in St Louis, St. Louis, Missouri 63130, USA. [2]Department of Biology, Bradley University, Peoria, Illinois 61625, USA.
E-mail: nstover@bradley.edu

DOI: 10.1016/j.cub.2006.12.002

Extra-Retinal Vision: Firing at Will

Recent evidence suggests that a key visual motion centre in the brain ignores extra-retinal motor information concerning reflexive eye movement. Instead it seems that neurons sensitive to oculomotor actions in this area fire at will.

Tom C.A. Freeman

Smooth eye movements create havoc in the images sent to the brain. As we track moving targets, pursuit eye movements destroy the link between real motion and image motion. Targets get glued to the centre of the image while other objects sweep across the retina (Figure 1). How does the visual system drive pursuit onwards and

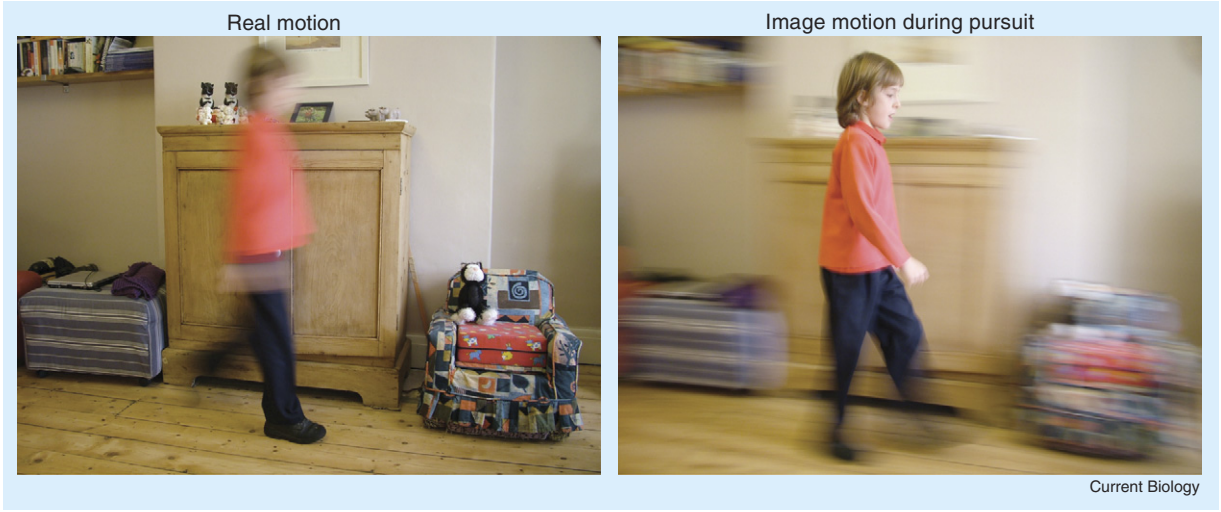

Figure 1. Pursuit eye movement destroys the link between real motion (left) and image motion (right).

how does it gauge the true velocity of objects? One solution is to use concurrent motor activity as a proxy for target motion. We know 'extra-retinal' information like this gets fed back at a number of key stages in the visual system. New work by Ono and Mustari [1] suggests that one of the main visual motion centres is quite discriminating about the type of extra-retinal signal it favours: reflexive eye movements are ignored; only deliberate eye movements will do.

Using single-cell recordings in the dorsal region of the medial superior temporal area (MSTd), Ono and Mustari [1] used the 'blink' paradigm to isolate a group of neurons sensitive to extra-retinal information. Monkeys were trained to track targets moving in the dark, some of which were briefly turned off and on as they moved across the screen. Pioneering work in other laboratories has shown that certain 'tracking' neurons in the lateral region of MST (MSTl) remain active during the blink [2–4]. Ono and Mustari [1] identified a similar group tracking neurons in MSTd and then examined what type of eye movement they prefer.

Pursuit eye movements are under our own control — for instance, a pedestrian standing at a busy crossing can choose which car to track. When we move about, however, a more reflexive type of eye movement helps stabilise the scene on the retina. Reflexive eye movements can be triggered in a number of ways, for instance by large regions of motion in the image or by physical movements of our head. When presented with a large moving stimulus it is virtually impossible to stop the eye moving. Similarly, shaking the head automatically triggers the vestibulo-ocular reflex, causing our eyes to counter-rotate.

Ono and Mustari [1] investigated how MSTd's tracking neurons responded during either pursuit or head rotation. Figure 2 shows the four conditions they investigated. In the pursuit condition (bottom right), a visual target moved back and forth and monkeys were trained to track it. In two head-rotation conditions, the monkey's chair was rotated back and forth, either in the dark or with a visible fixation point (bottom, middle and left). Eye movements in all three conditions were virtually identical. Despite this MSTd's tracking neurons only responded during pursuit. Intriguingly, they also responded when the fixation point rotated with the chair (a bit like trying to following the tip of one's nose as the head rotates; Figure 2, top left). As the graph shows, the correlation between mean firing rate in this condition and mean firing rate during pursuit was remarkably close. But the eye movements were very different. During pursuit the eyes moved in the skull, but when fixating the rotating target they did not. To achieve the latter a deliberate counteracting 'pursuit' command is used to cancel the vestibulo-ocular reflex. MSTd's tracking neurons seem to fire at will.

What are the functional reasons for encoding intended eye movement? The results with a rotating target suggests that MSTd's tracking neurons may represent a more sophisticated visual code than one simply helping to maintain pursuit. Tracking a moving object requires the observer to coordinate head and eye movement. Pursuit without head movement is one of many possible combinations that can redirect gaze. So is head movement without eye rotation. Whatever the combination, following a moving target always destroys the link between real motion and image motion. Tracking neurons may therefore be part of the network that helps recover the link. In contrast, reflexive eye movements stabilise images of scenes that for the most part are already stationary. When stabilisation is accurate, image motion and real motion line up — no compensation is required.

Tracking neurons are well placed to contribute to the compensation network. MST is a key visual motion centre, containing cells sensitive to many different types of image motion. Cells in MSTl prefer object movement over

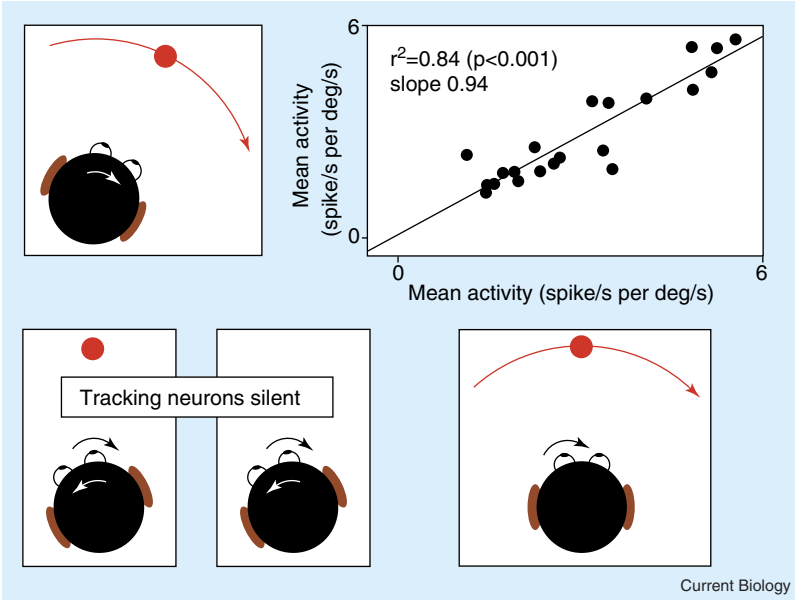

Figure 2. MSTd tracking neurons respond when gaze is redirected either by pursuit (all eye movement, bottom right) or head rotation (no eye movement, top left).

The graph shows mean activity is very well correlated. Conversely, tracking neurons are insensitive to the reflexive gaze stabilisation induced by head rotation, despite the fact that the eye rotates in the skull (bottom middle and right). (Adapted with permission from [1].)

textured backgrounds, seemingly encoding relative motion between figure and ground [5]. Lesions in MSTl also show a more pronounced disruption of pursuit eye movement than in MSTd [6], suggesting an explicit link between the tracking neurons found in MSTl and eye-movement control. Cells in MSTd, on the other hand, prefer more global patterns of motion, such as image expansion that is typical of locomotion through the world [7–9]. Microstimulation in this area produces predictable changes in perceived locomotion direction [10]. Moreover, MSTd neurons showed a preference for the true direction of locomotion as opposed to the distorted direction the eye movement produces in the image [11].

Human observers report a number of perceptual phenomena that could be explained by the type of behaviour displayed by MSTd's tracking neurons. The world wobbles when we gently poke an eye, an act that moves both eye and image. Clearly our capacity to differentiate between real motion and image motion can be compromised — and it is tempting to suggest that the absence of an oculomotor command leaves tracking neurons silent and image motion unchallenged. Other phenomena leave extra-retinal signals in a similar predicament. When placed in a rotating chair we easily counter the vestibulo-ocular reflex but experience an oculogyral illusion. Thus a fixation target moving with our head (Figure 2, top left) seems to rotate faster than the chair, as though the command we used to inhibit the reflex leaks into motion perception [12]. MSTd's tracking neurons are ideal candidates for the location of this leak.

In a similar vein, we experience illusory motion of a stationary target after adapting to repetitive eye movement [13]. Fixating the target requires a similar inhibitory command because if left in the dark the eyes would continue to move — so again, the inhibitory command seems to leak into perception. Moreover, only deliberate eye movements produce an aftereffect that 'stores' across a period of darkness [14]. The storage of motion aftereffects has been linked to the vicinity of MST [15]. Perhaps repetitive pursuit adapts MSTd's tracking neurons because of their preference for firing at will.

References

1. Ono, S., and Mustari, M.J. (2006). Extra-retinal signals in MSTd neurons related to volitional smooth pursuit. J. Neurophysiol. *96*, 2819–2825.
2. Ilg, U.J., Schumann, S., and Thier, P. (2004). Posterior parietal cortex neurons encode target motion in world-centred coordinates. Neuron *43*, 145–151.
3. Newsome, W.T., Wurtz, R.H., and Komatsu, H. (1988). Relation of cortical areas MT and MST to pursuit eye movements. II. Differentiation of retinal from extra-retinal inputs. J. Neurophysiol. *60*, 604–620.
4. Sakata, H., Shibutani, H., and Kawano, K. (1983). Functional properties of visual tracking neurons in posterior parietal association cortex of the monkey. J. Neurophysiol. *49*, 1364–1380.
5. Eifuku, S., and Wurtz, R.H. (1998). Reponse to motion in extrastriate area MSTl: Center-surround interactions. J. Neurophysiol. *80*, 282–296.
6. Dursteler, M.R., and Wurtz, R.H. (1988). Pursuit and optokinetic deficits following chemical lesions of cortical area MT and MST. J. Neurophysiol. *60*, 940–965.
7. Tanaka, K., and Saito, H. (1989). Analysis of moiton of the visual field by direction, expansion/contraction, and rotation cells clustered in the dorsal part of medial superior temporal area of the macaque monkey. J. Neurophysiol. *62*, 626–641.
8. Gu, Y., Watkins, P.V., Angelaki, D.E., and DeAngelis, G.C. (2006). Visual and nonvisual contributions to three-dimensional heading selectivity in the medial superior temporal area. J. Neurosci. *26*, 73–85.
9. Duffy, C.J., and Wurtz, R.H. (1991). Sensitivity of MST neurons to optic flow stimuli. I. A continuum of response selectivity to large-field stimuli. J. Neurophysiol. *65*, 1329–1345.
10. Britten, K.H., and van Wezel, R.J.A. (1998). Electrical microstimulation of cortical area MST biases heading perception in monkeys. Nat. Neurosci. *1*, 59–63.
11. Bradley, D.C., Maxwell, M., Andersen, R.A., Banks, M.S., and Shenoy, K.V. (1996). Mechanisms of heading perception in primate visual cortex. Science *273*, 1544–1547.
12. Evanoff, J.N., and Lackner, J.R. (1987). Influence of maintained ocular deviation on the spatial displacement component of the oculogyral illusion. Percept. Psychophys. *42*, 25–28.
13. Chaudhuri, A. (1991). Eye-movements and the motion aftereffect - alternatives to the induced motion hypothesis. Vision Res. *31*, 1639–1645.
14. Freeman, T.C.A., and Sumnall, J.H. (2005). Extra-retinal adaptation of cortical motion-processing areas during pursuit eye movements. Proc. R. Soc. Lond. B *272*, 2127–2132.
15. Culham, J.C., Dukelow, S.P., Vilis, T., Hassard, F.A., Gati, J.S., Menon, R.S., and Goodale, M.A. (1999). Recovery of fMRI activation in motion area MT following storage of motion aftereffect. J. Neurophysiol. *81*, 388–393.

School of Psychology, Cardiff University, Tower Building, Park Place, Cardiff CF10 3AT, UK.
E-mail: freemant@cardiff.ac.uk

DOI: 10.1016/j.cub.2007.01.020